# An anti-correlation between X-ray luminosity and Hα equivalent width in X-ray binaries

R. P. Fender[1,2], D.M. Russell[1,2], C. Knigge[1], R.Soria[3], R.I. Hynes[4], M.Goad[5]

[1] *School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ*
[2]*Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Kruislaan 403, 1098 SJ, Amsterdam, The Netherlands*
[3] *Mullard Space Science Laboratory (UCL), Holmbury St Mary, Dorking, Surrey RH5 6NT*
[4] *Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803*
[5] *Department of Physics and Astronomy, University of Leicester, LE1 7RH*

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**ABSTRACT**

We report an anticorrelation between continuum luminosity and the equivalent width (EW) of the Hα emission line in X-ray binary systems. The effect is evident both in a universal monotonic increase in Hα EW with time following outbursts, as systems fade, and in a comparison between measured EWs and contemporaneous X-ray measurements. The effect is most clear for black hole binaries in the low/hard X-ray state, which is prevalent at X-ray luminosities below $\sim 1\%$ Eddington. We do not find strong evidence for significant changes in line profiles across accretion state changes, but this is hampered by a lack of good data at such times. The observed anti-correlation, highly significant for black hole binaries, is only marginally so for neutron star systems, for which there are far less data. Comparison with previously established correlations between optical and X-ray luminosity suggest that the line luminosity is falling as the X-ray and optical luminosities drop, but not as fast (approximately as $L_{\mathrm{H}\alpha} \propto L_{\mathrm{X}}^{\sim 0.4} \propto L_{\mathrm{opt}}^{\sim 0.7}$). We briefly discuss possible origins for such an effect, including the optical depth, form of the irradiating spectrum and geometry of the accretion flow. Further refinement of the relation in the future may allow measurements of Hα EW to be used to estimate the luminosity of, and hence the distance to, X-ray binary systems. Beyond this, further progress will require a better sample of spectro-photometric data.

**Key words:** Accretion, accretion discs – X-rays: binaries

## 1 INTRODUCTION

The process of accretion is the power source driving the luminosities for a wide range of objects, including protostars, binary systems containing accreting white dwarfs, neutron stars or black holes, gamma ray bursts and supermassive black holes in active galactic nuclei. A comprehensive review of this process is provided by Frank, King & Raine (2002).

In most of these systems, most of the time, the accretion process proceeds via an accretion disc which transports angular momentum outwards and matter inwards. The temperature of this disc increases towards the centre, and is a function of accretion rate and central accretor mass. The disc may also produce (or even be partially replaced by) at various times a relatively cool disc wind, a very hot corona and a collimated relativistic outflow or 'jet'. Finally, the 'state' of the accretion flow at the centre of the disc may vary dramatically indicating rapid variations between phases with different geometries, temperatures and outflows. Reviews of observation of accretion onto white dwarfs, neutron stars and black holes

in binary systems can be found in e.g. Warner (2003) and Lewin & van der Klis (2006).

In X-ray binary systems containing an accreting neutron star or black hole the region of the accretion disc responsible for the optical continuum and emission lines lies at a large distance from the central accretor (several light seconds, or $\geq 10^4$ gravitational radii – e.g. Hynes et al. 2006). Many such systems are transients, in that they display phases of very high luminosities lasting typically weeks to months, followed by long periods in quiescence (e.g. Chen, Shrader & Livio 1997). Such cycles are likely to have their origin in accretion disc instabilities associated with hydrogen ionization (Frank et al. 2002 and references therein).

It is widely accepted that the emission lines in such systems arise in the rotating accretion disc flow. The strongest evidence for this interpretation is in the form of twin-peaked line profiles (e.g. Horne & Marsh 1986; Charles & Coe 2006 and references therein). The dominant pumping mechanism for these lines is likely to be irradiation by the central X-ray source at high luminosities, as is observed for the optical continuum (van Paradijs & McClintock

1994). At lower luminosities viscous heating of the disc may contribute significantly.

However, the picture may not be so simple. Russell et al. (2006 and references therein) have demonstrated that in black hole X-ray binaries (BHXBs) in 'hard' X-ray states synchrotron emission from the jet dominates the continuum in the near-infrared and can contribute significantly in the optical band. Wu et al. (2001, 2002) argue for three distinct origins for the emission line depending on the source luminosity and spectral states. In their model, in bright/soft X-ray states the line arises in the atmosphere of an optically thick disc, whereas in bright/hard X-ray states the H$\alpha$ line arises in a dense outflow. In the faintest quiescent states the whole accretion flow is optically thin.

In a related work, Eikenberry et al. (1998) found a near-linear correlation between Br$\gamma$ (2.166 $\mu$m) integrated line flux and the adjacent continuum flux density in the black hole X-ray binary GRS 1915+105, during phases when the continuum was likely to be synchrotron emission from the powerful jet in this source. This suggests radiative pumping of the lines by UV emission from the jet. Comparison with phases of soft X-ray spectra with no jet emission in the same study were taken to indicate that the jet is a far better source of photoionising photons than the inner accretion disc, presumably due to the fact that the ultraviolet-emitting region of the jet is raised above the disc and illuminates it very efficiently (this argument does not work if this region of the jet is moving relativistically away from the disc and therefore strongly Doppler de-boosted). However, a strong change in H$\alpha$ EW associated with X-ray state, and therefore jet production, is *not* observed in GX 339-4 (Wu et al. 2001; see also Fig 1), possibly arguing against strong pumping of H$\alpha$ by the jet.

In this paper we have compiled measurements of the strength of H$\alpha$, the most prominent emission line in the optical spectra of X-ray binaries. Our goal was to see how the properties of the emission line varied, if at all, with accretion 'state' and luminosity of X-ray binary systems, and whether or not there was clear evidence for phases where the lines were formed in an outflow rather than a disc. What we find is evidence for an anti-correlation between the equivalent width (ratio of line to local continuum flux) and overall luminosity of such systems, in particular when in the 'hard' X-ray state (at luminosities below about 1% of the Eddington limit).

## 2  AN ANTI-CORRELATION BETWEEN H$\alpha$ EW AND LUMINOSITY IN BLACK HOLE X-RAY BINARIES

Two approaches, discussed below, are taken in order to investigate the relation between emission line strength and luminosity in black hole X-ray binaries. In the first we track the equivalent width (EW) of H$\alpha$ as a function of time following an X-ray outburst, in which case the general trend of the relation with luminosity is inferred (albeit quite confidently); in the second approach we directly compare H$\alpha$ EW with X-ray luminosity, a more direct approach but one which is limited by a lack of data at low luminosities.

Before doing so, we present in Fig 1 optical spectra in the H$\alpha$ region for the black hole X-ray binary GX 339-4 in three 'states': a very faint state (upper spectrum), a bright state with a hard X-ray spectrum (middle spectrum) and a bright state with a soft X-ray spectrum (lower spectrum). What is immediately clear is that in the faint state the H$\alpha$ EW is much greater than it is in either of the higher-luminosity states, and also that there does not appear to be much change in the line EW (or profile) between the two high-luminosity states. Indications of the optical magnitudes and EWs
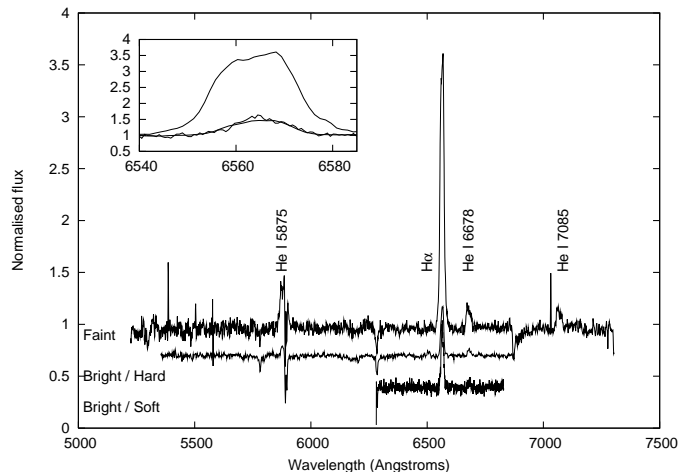


**Figure 1.** Normalised optical spectra of GX 339-4 in low luminosity, bright/hard (-0.3 in normalisation) and bright/soft (-0.6) states (Soria, Wu & Johnston 1999; Shahbaz, Fender & Charles 2001). These spectra are almost certainly uncontaminated by a companion star. The strongest emission line is H$\alpha$, which clearly has a much greater equivalent width in the faint state than in either of the brighter states. The inset shows the H$\alpha$ profile for all three spectra plotted on the same scale. The bright/hard and bright/soft spectra, with H$\alpha$ EW $\sim -7$Å were simultaneous with photometric observations which recorded $V \sim 16.5$; the faint state observations, with H$\alpha \sim -55$ Å were obtained when $R = 20.1 \pm 0.1$.

at the different epochs are given in the figure caption. See Soria, Wu & Johnston (1999) and Shahbaz, Fender & Charles (2001) for a detailed discussion of these spectra.

### 2.1  Trends of increasing H$\alpha$ EW during outburst decays

Most X-ray transients (with both black hole and neutron star accretors) follow a monotonic decay (with some occasional rebrightenings) in X-ray luminosity after the first few weeks or months of outburst. Specifically, Chen, Shrader & Livio (1997) noted a mean exponential decay timescale for X-ray transients of around 30 days in the initial decline from outburst. Such a decay rate indicates that within 2 years a source should have returned to a 'quiescent' level, typically a factor $\sim 10^7$ fainter in $L_X$ than at the peak of outburst. As a caveat it should be noted that the observed decays are often far from simple exponentials. Nevertheless, a trend of increasing EW with time following outburst would therefore be a strong indicator that there is a luminosity – EW anti-correlation. This effect is investigated in Fig 2, where time evolution of H$\alpha$ equivalent width is plotted for the first 1000 days following outburst, for six BHXBs, which for most sources should include the return to quiescence. The dates and references for these outbursts are given in Table 1. These were the only six sources for which we could find good coverage of the H$\alpha$ EW following the outburst. A clear trend of increasing EW with time is observed in the first four sources (GRO J0422+32, GS 1124-68, A0620-00, XTE J1118+480), following an intial period of erratic variations or dips, which probably corresponds to points before the monotonic decay had begun. The fifth source, XTE J1550-564 shows a similar pattern of behaviour, but there are hints, at around 1000 days, of a subsequent decline in the EW. Inspection of the RXTE ASM monitoring at this time does not reveal any obvious subsequent outburst, but is not sensitive to activity below $L_X \sim 10^{36}$ erg s$^{-1}$. However, optical monitoring reported by Orosz et al. (2002) does in fact indicate that this final

| Source | References |
|---|---|
| **Black hole binaries** | |
| GRO J0422+32 | Callanan et al. 1995, Bonnet-Bidaud & Mouchet 1995, Garcia et al. 1996, Casares et al. 1995, Harlaftis et al. 1999 |
| A 0620-00 | Whelan et al. 1977, Murdin et al. 1980, Marsh, Robinson & Wood 1994 |
| XTE J1118+480 | Torres et al. 2004, Zurita (private communication) |
| GS 1124-68 | Orosz et al. 1994, della Valle et al. 1998, Casares et al. 1997, Sutaria et al. 2002, Ebisawa et al. 1994 |
| XTE J1550-564 | Orosz et al. 2002, Sanchez-Fernandez et al. 1999, Casares, Dubus & Homer 1999, Buxton et al. 1999 |
| GRO J1655-40 | Bianchini et al. 1997, Shahbaz et al. 2000, Soria et al. 2000 |
| GX 339-4 | Grindlay 1979, Soria, Wu & Johnston 1999, Shahbaz, Fender & Charles 2001 |
| GS 2000+25 | Charles et al. 1988, Shahbaz et al. 1996, Tsunemi et al. 1989, Casares et al. 1995, Garcia et al. 2001 |
| XTE J1650 | Augusteijn et al. 2001, Sanchez-Fernandez et al. 2002 |
| XTE J1859+226 | Garnavich et al. 1999, Wagner et al. 1999, Zurita et al. 2002 |
| GRS 1009-45 | della Valle et al. 1997 |
| V404 Cyg | Casares et al. 1991, 1993, Hynes et al. (2004) |
| 4U 1957+11 | Shahbaz et al. 1996 |
| **Neutron star binaries** | |
| Aql X-1 | Charles et al. 1980, Shahbaz et al. 1996, Garcia et al. 1999, Shahbaz et al. 1998 |
| Cen X-4 | van Paradijs et al. 1980 and 1987, Shahbaz et al. 1996, Campana et al. 2004 |
| Sco X-1 | Shahbaz et al. 1996 |
| Cyg X-2 | Shahbaz et al. 1996 |
| EXO 0748-676 | Pearson et al. 2006 |
| IGR 00291+5934 | Torres et al. 2004, Filippenko et al. 2004 |
| SAX J1808.4-3658 | Campana et al. 2004, Campana & Stella 2004 |
| XTE J1814-338 | Steeghs 2003, Papitto et al. 2007 |
| HETE J1900.1-2455 | Elebert et al. 2008 |
| XTE J2123-058 | Casares et al. 2002, Tomsick et al. 2004 |

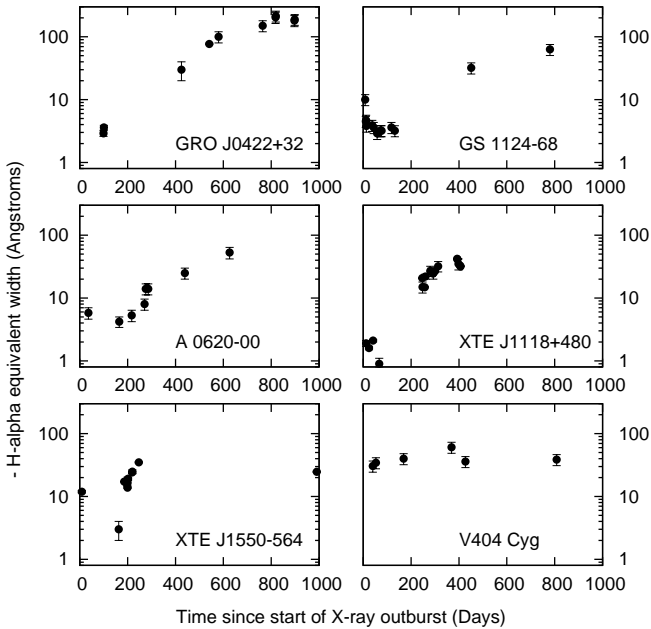**Table 1.** X-ray binaries used in this study, with relevant references.



**Figure 2.** Variation of Hα equivalent width (EW) with time since X-ray discovery of six transient black hole binaries. For the top four sources, GRO J0422+32, GS 1124-68, A0620-00, XTE J1118+480, there is a clear increase in the EW with time. For XTE J1550-564 there is an initial increase but hints of a subsequent decline, and for V404 Cyg there is no clear trend. Assuming this is a representative sample, this strongly suggests an anti-correlation of EW with luminosity as the majority of black hole transients fade following outbursts.
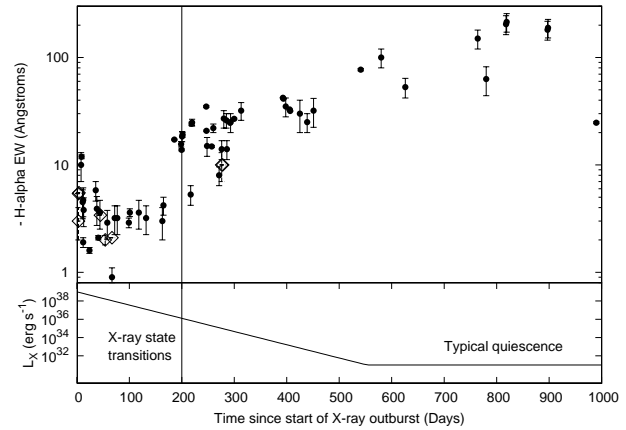


**Figure 3.** The data for the first five sources in Fig 1 overplotted (filled circles), plus a small number of additional measurements (open diamonds; see text for details). The similarity in the post-outburst time evolution of the Hα EW is remarkable. In the lower panel is a crude approximation of the X-ray luminosity evolution of the source based upon the typical exponential decay timescale for transients (Chen, Shrader & Livio 1997) and typical quiescent level (Remillard & McClintock 2006 and references therein). The vertical line at 200 days delay indicates the time after which all the sources should be in the hard spectral state; at earlier times they could be in either soft or hard X-ray states (Maccarone 2003; Homan & Belloni 2005).

EW measurement was within 200 days of an additional optical outburst; therefore its behaviour may not be discrepant. Note that for some of the other sources there is evidence in the literature for minor rebrightenings after 200 days which should not affect the broad

conclusions here but may have some relevance for the poorer anti-correlation between X-ray luminosity and quasi-simultaneous EW measurements in the next section. Finally in the sixth panel V404 Cyg, which was in several ways an unusual transient (e.g. Kitamoto et al. 1989) and is far more luminous in 'quiescence' than most BHXBs, does not display any clear trend of increasing EW following its outburst.

Therefore, it does seem that for the majority (5 of 6) of the sources, there is an increase in Hα EW following outburst, which strongly suggests an anti-correlation between luminosity and Hα EW in these systems. We have no reason to believe that our sample is strongly biased, but the sample of available EW data is clearly small and it is probably too early to quantify the diversity in these general EW trends.

In Fig 3 we overplot the data for the first five sources from Fig 2; i.e. all except V404 Cyg. The Spearman rank correlation coefficient for the increase in EW with time for the sample of all six sources is $r_s = 0.82$, a rank correlation at the $6.8\sigma$ level. Removing V404 Cyg, the most discrepant source and arguably a 'non-standard' transient (i.e. the data set plotted in Fig 3), increases these figures slightly to $r_s = 0.89$, corresponding to a rank correlation at the $7.1\sigma$ level. Adding a small number of additional points for the sources GS 2000+25, XTE J1650-500, XTE J1859+226 and GRS 1009-45 increases the significance of the correlation to $7.3\sigma$ (see Table 1 for references). Table 2 presents a compilation of the Spearman rank correlation coefficients and their significance for most of the samples discussed in this paper.

Fig 3 does however also hint at a complication to the picture, namely that the correlation between elapsed time and Hα EW is clearer after about 200 days, which is around the time that most sources are expected to have made a transition back to the hard X-ray spectral state, at a (2–10 keV) X-ray luminosity of a few $\times 10^{37}$ erg s$^{-1}$ (Maccarone 2002; Homan & Belloni 2005). At this point the steady, powerful jet associated with this state is expected to be reactivated after a period in the soft X-ray state in which it was suppressed (Fender, Belloni & Gallo 2004 and references therein). In order to investigate this effect we separated the data from Fig 3 at the point of 200 days (vertical line in Fig 3). The data after this point, almost certainly exclusively in the hard X-ray state, still showed a significant correlation between elapsed time and the Hα EW at the $5.1\sigma$ level ($r_s = 0.80$). The sample of data prior to 200 days were not significantly correlated in any way with the elapsed time. The increase in overall significance for the entire sample can be attributed to the combination of the correlation in the hard X-ray state together with a generally lower EW in the 'clump' of data at shorter elapsed times, which will include a mix of luminous hard and soft X-ray states. Fig 3 is a log-linear plot, therefore it is clear from the apparent linear relation that an exponential fit should be appropriate. A fit to the ensemble of data from 200 days onwards (excluding V404 Cyg), i.e. almost certainly in the hard state, indicates an e-folding time constant for the increase of Hα EW of $286 \pm 23$ days. If the 30 days e-folding decay time for the X-ray luminosity were an accurate estimate, then this would imply that EW $\propto L_X^{-0.1}$ (approximately). We will test this in the next section. Note that the global correlation between X-ray and optical luminosities for BHXBs reported in Russell et al. (2006; see also van Paradijs & McClintock 1994) demonstrates that any anti-correlation found, or inferred, between EW and X-ray luminosity, is also one between EW and optical luminosity (hence the use of the generic term 'luminosity' in much of what follows).

| Source | EW vs. time | EW vs. $L_X$ |
|---|---|---|
| GRO J0422+32 | 0.90 (2.7$\sigma$) | -0.90 (1.8$\sigma$) |
| GS 1124-68 | -0.10 (0.3$\sigma$) | |
| A 0620-00 | 0.92 (2.4$\sigma$) | -0.56 (1.1$\sigma$) |
| XTE J1118+480 | 0.94 (4.2$\sigma$) | |
| XTE J1550-564 | 0.93 (2.9$\sigma$) | -0.91 (2.9$\sigma$) |
| V404 Cyg | 0.54 (1.2$\sigma$) | |
| GX 339-4 | | -0.49 (1.1$\sigma$) |
| GRO J1655-40 | | 0.41 (1.7$\sigma$) |
| BH Ensemble | 0.82 (6.8$\sigma$) | -0.48 (3.9$\sigma$) |
| NS Ensemble | – | -0.68 (2.3$\sigma$) |
| BH+NS Ensemble | – | -0.58 (5.1$\sigma$) |

**Table 2.** Spearman rank correlation coefficients, and their significance in terms of standard deviations, for the relation of Hα equivalent width as a function of time since outburst (column 2) and X-ray luminosity (column 3). The ensemble values are presented in the last row. Gaps indicate sources for which there are too little data to make meaningful tests.
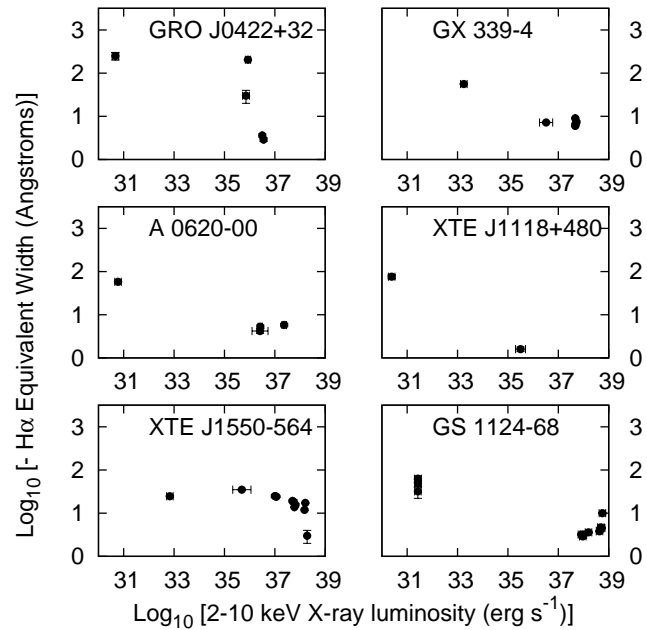


**Figure 4.** Variation of Hα EW with estimated X-ray luminosity based on contemporaneous observations. The sources are the same as presented in Fig 2, except that V404 Cyg has been replaced with GX 339-4. All sources show a general anti-correlation, although the patterns of behaviour are clearly not identical.

## 2.2 EW as a function of X-ray luminosity

The approach taken in section 2.1, in plotting Hα EW as a function of time for BHXBs is a strong but indirect indication of an anti-correlation of the EW with luminosity. A more direct comparison of luminosity and EW would be desirable, to rule out some unexpected mechanism rather than luminosity changes dominating the observed effect. Unfortunately, the majority of the optical spectroscopic observations do not appear to be well flux-calibrated, so we cannot directly compare EW with optical continuum luminosity.

A second possibility is to compare with an X-ray measurement which has been made contemporaneously, which is what we
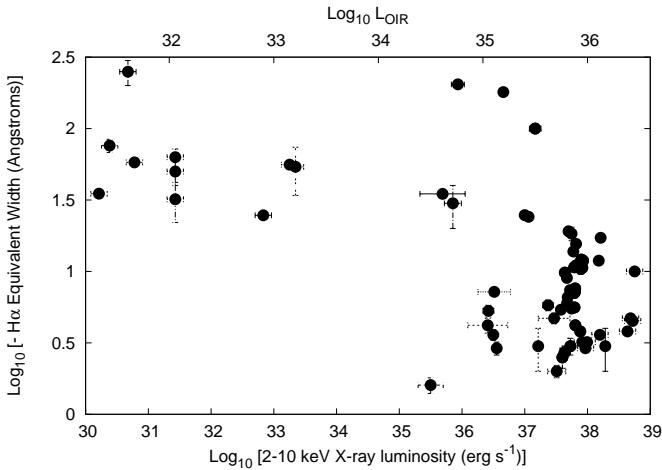
**Figure 5.** Hα equivalent width (EW) as a function of contemporaneously measured X-ray luminosity (typically 2–10 keV). All the data from Fig 4 are combined, as well as a small number of additional measurements (see text for details). There is an overall rank anti-correlation, at a $3.9\sigma$ confidence level. The upper x-axis indicates an estimate of the optical–infrared luminosity, $L_{\mathrm{OIR}}$, calculated from the relation $L_{\mathrm{OIR}} = 10^{13.2} L_X^{0.60}$ for black hole binaries presented in Russell et al. (2006).

**Figure 6.** As Fig 5, but for neutron star binaries (the black hole sample from Fig 5 are indicated as small dots). These points are consistent with neutron star X-ray binaries following a similar anti-correlation to black hole binaries (with a hint of a lower normalisation). As in Fig 4, the upper x-axis indicates an estimate of $L_{\mathrm{OIR}}$ based upon the relation from Russell et al. (2006), which is $L_{\mathrm{OIR}} = 10^{9.7} L_X^{0.66}$, slightly different to that for black holes (hence the slightly different range in $L_{\mathrm{OIR}}$).

attempt next. In order to be considered, the X-ray and optical spectroscopic measurements had to be made within one day of each other, except at quiescent levels at which we assumed a more or less stable level had been reached (quiescent variability can reach factors of several, but this not very significant for these logarithmic plots). In Fig 4 we plot Hα EW as a function of $L_X$ for the sample of objects discussed previously (except for V404 Cyg for which we do not have contemporaneous X-ray measurements), plus the more unusual object GX 339-4. None of the individual sources show a statistically significant rank (anti-)correlation (see Table 2). In Fig 5 we plot the ensemble of data points, plus a small amount of additional data from the sources V404 Cyg, GRO J1655-40, 4U 1957+11, GS 2000+25, XTE J1650-500 and XTE J1859+226 (see Table 1 for references).

A Spearman rank correlation test for the complete sample plotted in Fig 5 results in a Spearman rank correlation coefficient of $r_s = -0.48$ (a $\sim 3.9\sigma$ result). This supports the conclusion of section 2.1. A single power-law fit to the data presented in Fig 5 gives

$$EW = (-24 \pm 18) \frac{L_X}{10^{36}}^{-0.18 \pm 0.06}$$

This is close to, but steeper than, the EW $\propto L_X^{-0.1}$ estimated in section 2.1, and indicates a mean X-ray decay e-folding time less than the 30 days given in Chen et al. (1997). The apparent anti-correlation seems to be dominated by the difference between measurements at $L_X \leq 10^{36}$ erg s$^{-1}$, where all sources are in the hard X-ray spectral state, and those at higher luminosities, where transitions between different spectral states can occur (see e.g. Nowak 1995; Homan & Belloni 2005; Remillard & McClintock 2006 for a discussion of these states).

It is somewhat puzzling that the anti-correlation stands out much more clearly in the first analysis (Figs 2 and 3) than in the second (Figs 4 and 5), which implies that there may not be a simple one-to-one relation between X-ray luminosity and Hα EW. In this context it is interesting to note that the low-frequency QPOs in some hard state black hole candidates show similar monotonic be-
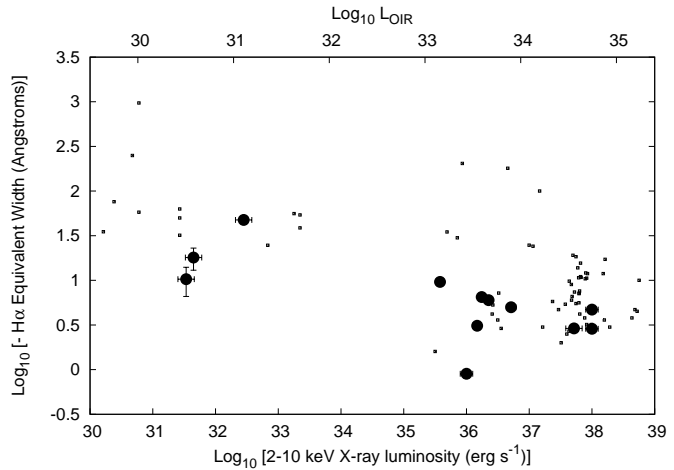
haviour with time which is not so simple when compared to X-ray flux (e.g. XTE J1118+480 in Wood et al. 2001). In any case, the anti-correlation, whether simple or not, is clearly there.

### 2.2.1 *Neutron star X-ray binaries*

Far fewer results were available in the literature for neutron star systems; the details and references are provided in Table 1. In Fig 6 we plot the neutron star data alongside the black hole data presented in Fig 5. What we see is approximately similar behaviour, in that there is a suggestion of a similar trend, with a similar (or slightly lower) normalisation. In fact a Spearman rank correlation test indicates that the sample of seven neutron star measurements are anticorrelated at the $2.7\sigma$ level ($r_s = -0.84$). So the neutron star data are consistent with, but do not independently establish, the anti-correlation found for the BHXBs.

Adding the BHXB and neutron star samples results in a Spearman rank correlation coefficient of $r_s = -0.58$, corresponding to an anticorrelation at the $5.1\sigma$ level.

In summary, although the individual simultaneous $L_X$ and EW measurements do not confirm the anti-correlation further, the effect is significant when considering the ensemble of all data points, moreso when combining neutron star data with the black hole sample.

### 2.3 Relation to optical continuum luminosity

The upper x-axes of Figs 5 and 6 also indicate a rough estimate of the optical–infrared luminosities, $L_{\mathrm{OIR}} = \nu L_\nu$ based on the relations presented in Russell et al. (2006), and repeated in the figure captions (without statistical uncertainties). Note that the relations are slightly different for black holes and neutron stars ($L_{\mathrm{OIR}}$ is larger for black holes at any given X-ray luminosity). This allows us to get a better idea of how the EW varies as a function of the optical continuum.

Subject to caveats about the possibly complex nature of the relation to the lines, we can go further. By definition,

$$\text{EW} \propto \frac{L_{\text{H}\alpha}}{L_{\text{opt}}}$$

where $L_{\text{H}\alpha}$ and $L_{\text{opt}}$ are the line and continuum luminosities respectively. From Russell et al. (2006),

$$L_{\text{OIR}} \propto L_{\text{X}}^{c}$$

where the value of $c$ is slightly different for BH and NS systems. We also fit a crude relation of the form

$$\text{EW} \propto L_{\text{X}}^{d}$$

above. If we can assume $L_{\text{OIR}} \propto L_{\text{opt}}$ (i.e. $L_{\text{H}\alpha} << L_{\text{opt}}$ which is justified for a maximum EW of $\sim 100$ Angstroms and a filter width of $> 1000$ Angstroms, *and* a large fraction of the data in Russell et al. (2006) being in the R-band) we get

$$L_{\text{H}\alpha} \propto L_{\text{OIR}} L_{\text{X}}^{d}$$

Substituting, we get

$$L_{\text{H}\alpha} \propto L_{\text{X}}^{c+d} \propto L_{\text{opt}}^{1+(d/c)}$$

For the black holes, $c \sim 0.6$ and $d \sim -0.2$, resulting in

$$L_{\text{H}\alpha} \propto L_{\text{X}}^{\sim 0.4} \propto L_{\text{opt}}^{\sim 0.7}$$

Given the crudeness of the fit to the EW-$L_{\text{X}}$ relation, there seems little point in propagating uncertainties on these relations. While this analysis is crude, it does demonstrate that the H$\alpha$ line luminosity must vary quite strongly with X-ray luminosity, but not quite as fast as the continuum.

## 3  THE ORIGIN OF THE LINES AND CONTINUUM IN BHXBS

A key diagnostic of the emission site of a spectral line is the line profile itself. A twin-peaked line profile is a strong indication that the line originates in a rotating flow, such as the atmospheres of geometrically thin accretion discs (e.g. Horne & Marsh 1986; note however that Murray & Chiang 1996,1997,1998 have shown that accretion discs with winds can produce single-peaked lines).

In Fig 7 we indicate which lines, from the sample presented in Fig 5, were reported as twin-peaked. We see that twin-peaked line profiles have been reported at nearly all luminosities, which strongly suggests that the line-emitting region is ubiquitously associated with the rotating accretion flow. As already noted in the introduction, this is not universally accepted, and a more complex picture is put forward by Wu et al. (2001, 2002) who argue for three distinct origins for the emission line depending on the source luminosity and spectral states. In all cases, the optical continuum and lines are likely to be excited by irradiation from a central hot continuum source at least at high luminosities (see arguments in van Paradijs & McClintock 1994, and the more recent global study by Russell et al. 2006). As noted in the introduction, however, it has been suggested that the ionising source may in fact be (at times) associated with an outflowing jet or corona and not necessarily a static central X-ray source (see e.g. Eikenberry et al. 1998; Beloborodov et al. 1999; Markoff et al. 2005). Although we do not think it has an important impact on this analysis, we note that double-peaks may be filled in if the inclination is low or additional components produce low velocity emission. Similarly, single peaked profiles can also be mainly from a disc and vice-versa an intrinsic single peaked profiles with central absorption could give the appearance of a double-peaked line without needing a disc-like flow.

The observed anti-correlation between H$\alpha$ EW and X-ray luminosity (both direct and inferred) implies that as the X-ray luminosity decreases the optical continuum flux drops faster than the line flux. The analysis in section 2.3 above demonstrates that, over large luminosity ranges at least, all three quantities (X-ray luminosity, optical luminosity, H$\alpha$ line flux) are dropping, but at different rates (X-rays drop fastest, line flux slowest). The optical continuum in BHXBs appears to have contributions from both thermal emission from the outer, irradiated, accretion disc plus, in hard X-ray states, a component associated with optically thin synchrotron emission from a jet (Russell et al. 2006). The jet contribution is strongest at longer wavelengths, dominating in the infrared band, but probably contributes no more than 30% of the luminosity in the R-band (Corbel & Fender 2002; Homan et al. 2005; Russell et al. 2006), which contains the H$\alpha$ line.

Note that at low luminosities the companion star may begin to have a discernible contribution to the continuum luminosity of the systems. Russell et al. (2006) compile the estimated optical luminosities of several X-ray binaries, and find that in most systems the companion only contributes significantly in quiescence (i.e. $L_{\text{X}} \leq 10^{33}$ erg s$^{-1}$). Marsh et al. (1994) show how in the quiescent system A0620-00 the H$\alpha$ EW is modulated at the orbital period, presumably due to varying continuum contributions from the tidally distorted companion. We do not attempt in this paper to subtract such a contribution, noting that (i) over the range of luminosities covered in this compilation it is probably not a major effect, (ii) any contribution to the continuum by the companion would serve to *increase* the true disc EW at low luminosities and strengthen the anti-correlation were it taken into account. However, it is worth noting that in a regime in which an approximately constant continuum level is set by the companion, the true line flux may be proportional to the measured EW.

## 4  DISCUSSION

Based on a wealth of observational data, we have an approximate picture of how the emitted spectra and, to a lesser extent, central accretion/outflow geometry, might vary in BHXBs, principally as a function of luminosity. For example, it is known that an approximately steady jet is produced at relatively low accretion rates ($\dot{M}/\dot{M}_{\text{Edd}} \leq 0.01$) which are associated with hard X-ray spectra, whereas at higher accretion rates transitions to softer X-ray states with weaker jets can occur (Fender, Belloni & Gallo 2004; Homan & Belloni 2005). At lower accretion rates a simple relation between radio and X-ray luminosities appears to hold to at least $L_X/L_{\text{Edd}} \sim 10^{-8}$ (Gallo et al. 2006). There is however some evidence that the X-ray spectrum does soften at very low luminosities (Corbel, Tomsick & Kaaret 2006; Corbel, Körding & Kaaret 2008). In the case of accreting white dwarfs in cataclysmic variables, Williams (1980) argued that the outer region of the accretion discs may at some times be optically thick in the line but thin in the continuum. If a similar situation exists during the decay phase of X-ray transients outbursts, it may well contribute significantly to the observed EW anti-correlation.

The observed anti-correlation is likely to be due to some combination of these changes in the accretion / outflow geometry, the irradiating spectrum, and the optical depth in the outer accretion disc. A key question is whether or not there are changes in the line properties across the accretion state transitions. As noted earlier this was one of the key motivations for this research; however, our findings are inconclusive. On the one hand the line profile and EW
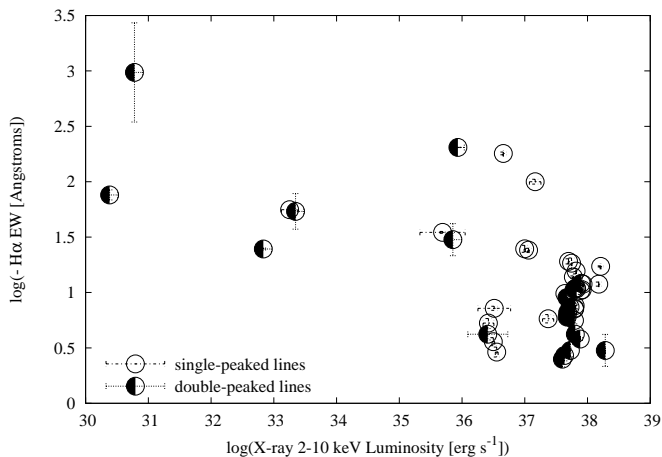
**Figure 7.** Observations in which twin-peaked Hα emission has been resolved. The detection of twin-peaked emission at all luminosities strongly suggests that the line always originates in a rotating accretion disc or optically thin accretion flow.

of Hα in GX 339-4 is clearly very similar in bright hard or soft states (Fig 1), but the analysis in section 2.1 suggests that the anti-correlation is better in the hard state below $\sim 0.01 L_{\mathrm{Edd}}$. Results for the black hole transient GRO J1655-40 presented in Shrader et al. (1996) also suggest a large increase in Hα EW across a soft $\rightarrow$ hard state transition, although the soft X-ray luminosity of the source would also have been fading during this period. The reader is reminded that Wu et al. (2001) claim that the line profile changes from hard to soft X-ray states.

### 4.1 Optical depth changes

A possible explanation for the observed anti-correlation is that a large part of the outer disc becomes cold enough to be optically thin in the continuum, not the line, during the decline (Williams 1980). In that case, the optical continuum drops much more quickly than the ionizing continuum from the inner region (where the inflow is still optically thick and producing strong continuum emission). As a result the EW of the optical lines from the outer (optically thin) region should increase. Such optically thin regions of the outer disc may well exist in X-ray binaries (e.g. Canizzo & Wheeler 1984). Shahbaz et al. (2004) discuss the possibility of regions of different optical depth contributing to the Hα and Hβ emission from the BHXB A0620-00 in quiescence. It is also possible that there is a saturation effect, in that during outbursts most of the accretion disc becomes too hot for the production of Hα line emission. The effect should therefore be different for higher excitation lines such as HeII.

### 4.2 Spectral and geometrical changes

Although the models mentioned above may well be responsible for the observed anti-correlation, studies over the past decade have indicated that the accretion flow in X-ray binaries, in particular black hole systems, undergo dramatic changes on short timescales which could well have an effect upon observed emission line profiles. For this reason we summarize this empirical understanding below, and comment on whether or not it might affect the observed anti-correlation.

If, as we assume, the Hα is a result of irradiation of the outer disc, then the main source of this irradiation will be EUV photons with energies between about 13 – 25 eV. These photons are not directly observable in nearly all black hole X-ray binaries, which lie at several kpc in the galactic plane and as a result suffer from strong interstellar extinction. Lower energy photons cannot ionise hydrogen, and photons with significantly higher energies (i.e. X-rays) are more likely to contribute to the reprocessed (reflection) continuum (e.g. Ross & Fabian 1993). We do not consider here the possibility of collisional excitation in e.g. an accretion disc hotspot.

How plausible is it that changes in the ionising spectrum are responsible for the observed anti-correlation? In bright soft states ($L_X \geq 0.01 L_{\mathrm{Edd}}$) the X-ray spectra of BHXBs are dominated by thermal (accretion disc) components with kT $\geq$ 1 keV. In less bright, but still very luminous ($10^{-4} L_{\mathrm{Edd}} \leq L_X \leq 10^{-2} L_{\mathrm{Edd}}$), hard X-ray states the X-ray spectrum is dominated by a component which peaks at $\sim 100$ keV and probably has its origin in a Comptonising 'corona' (e.g. Sunyaev & Titarchuk 1980), with some possible contributions from a jet (e.g. Markoff, Nowak & Wilms 2005). It should be noted that there can be strong hysteresis between spectral state and luminosity for $L_X \gtrsim 10^{-2} L_{\mathrm{Edd}}$ (Homan & Belloni 2005). As a source drops further in luminosity the accretion disc temperature should drop monotonically until in 'quiescence' ($L_X \sim 10^{-8.5} L_{\mathrm{Edd}}$) it is only about 1 eV (McClintock, Horne & Remillard 1995; McClintock et al. 2003). As noted above, at most X-ray luminosities this thermal disc component is essentially unmeasurable as it peaks at (E)UV wavelengths, in which band most distant galactic plane BHXBs cannot be observed. In the case of XTE J1118+480 (McClintock et al. 2003) this disc component was found to be significantly more luminous than the X-ray component when in quiescence. Therefore, at the lowest X-ray luminosities the bulk of the photons released by the accretion process are not able to ionise hydrogen, which – naively – should result in a reduced Hα EW at the lowest luminosities, *contrary* to what is observed. However, the optical continuum is also dominated by reprocessing and so the overall effect on EW will depend upon which component is pumped most effectively by the ionizing continuum, which in some sense returns us to the models dealing with the optical depth of the outer disc (e.g. Williams 1980).

What about changes in the geometry of the accretion flow and outflow with luminosity? Some recent sketches of the accretion flow as a function of luminosity for BHXBs (Esin, McClintock & Narayan 1997; Done, Gierlinski & Kubota 2007) suggest that as luminosity increases the ability of the central hard X-ray source to illuminate the disc is reduced, as the coronal component shrinks. Geometries which include jets (e.g. Fender, Belloni & Gallo 2004; Ferreira et al. 2006) may be more complete, although it is unclear how significantly any X-ray emission from the jet could contribute to irradiation of the accretion disc or its atmosphere (Markoff, Nowak & Wilms 2005). Such X-ray emitting regions near the base of the jet may be essentially indistinguishable from an outflowing corona (e.g. Beloborodov 1999). Nevertheless, it has been suggested that the velocity of the outflow from X-ray binaries may increase with luminosity, and in a more complex way with spectral state. If the jet or outflowing corona is responsible for some irradiation of the disc, then an increase in velocity with luminosity could result in a reduced Hα EW as an increasing fraction of the X-rays are beamed along the direction of motion, away from the disc.

## 5   CONCLUSIONS

A prime motivation for this research was to investigate whether the profiles of optical emission lines change significantly across the accretion state transitions in X-ray binary systems. Such a result may have indicated a strong response to a changing irradiating spectrum and/or geometry of the line-emitting region. However, the results in this respect remain inconclusive.

What we did find, and report in detail, is an anti-correlation between the broadband luminosity (optical – X-ray) and the equivalent width of the H$\alpha$ emission line in X-ray binaries. Possibly the most closely related phenomenon already known is a comparable anti-correlation in the H$\beta$ line for Cataclysmic Variables (Patterson 1984; see also Witham et al. 2006), accreting binaries hosting a white dwarf rather than a black hole or neutron star. Patterson (1984) compares this result with the models of Tylenda (1981), which are similar to those of Williams (1980) in which the outer accretion disc becomes optically thin at low luminosities. This may also turn out to be the appropriate explanation for the X-ray binaries under discussion here, but the complex and hysteretical accretion state changes about which we have learned much in the past decade caution us against drawing such a conclusion at this time. More detailed observations of line profiles across state transitions would clearly be of interest. The reader is further reminded that (i) rebrightenings during the decay of transients, (ii) the monotonic behaviour of QPOs in sources such as XTE J1118+480 despite varying behaviour in $L_X$, and (iii) the poorer anticorrelation of EW with quasi-simultaneous $L_X$ than with time all suggest that the causal link between luminosity and EW may be complex.

It it worth mentioning in passing the similarity with the Baldwin Effect observed in accretion flows around supermassive black holes (Baldwin 1977; see also e.g. Mushotzky & Ferland 1984). In this case an anti-correlation is observed between the EW some lines originating in the broad line region (BLR) and the continuum luminosity. A related effect is observed in the X-ray band (Iwasawa & Taniguchi 1993; Page et al. 2004), and maybe also in the strong stellar winds of Wolf-Rayet stars (Morris et al. 1993). However, there is little evidence for a BLR-like region in X-ray binary systems, probably due to the high ionisation state of the gas in the inner disc region (e.g. Proga, Kallman & Stone 2000). Therefore the physical origins of the two effects are almost certainly rather different.

Further observations would obviously be of interest to understand better this effect. These should include observations of other lines and in other bands. Observations in the near-infrared, where the continuum should have a much stronger jet contribution (e.g. Corbel & Fender 2002; Russell et al. 2006) should show a much stronger reaction to accretion state changes (e.g. we would expect a large jump in EW of a line like Br $\gamma$ as the jet switches off in a hard $\rightarrow$ soft state transition). It is interesting to note that the spectra in Fig 1 hint at a similar anti-correlation for HeI, and HeII would be even more interesting, given the higher ionisation potentials. The observed anti-correlation holds the promise of being able to estimate the luminosity of a source from the H$\alpha$ EW, something which could prove invaluable in distance determinations for faint X-ray binaries. However, the relation obviously needs to be significantly improved before that is possible, and may turn out to have enough intrinsic scatter to reduce its usefulness in this aspect (as is in fact the case for the Baldwin Effect in AGN). In any case it is promising that low-luminosity accreting sources should be clearly identifiable in e.g. H$\alpha$ surveys by their large equivalent widths.

Finally, it is interesting to note that observations of the variation of the H$\alpha$ line strength with luminosity may in fact be our best way to track the behaviour of the accretion disc component at intermediate luminosities. Below $L_X \sim 10^{-3} L_{\rm Edd}$ the accretion disc component peaks in the (E)UV spectral regime and is unobservable for nearly all sources. For two sources only has it been observed in quiescence, at which point it appears that it no longer extends to the ISCO but is truncated (McClintock et al. 1995, 2003). Although well-defined models exist (e.g. Dubus, Hameury & Lasota 2001), exactly how and where this truncation begins is observationally very uncertain (e.g. Miller et al. 2006). However, since the H$\alpha$ line responds preferentially to photons of energies 13–25 eV, it may be the best way to study the evolution of this disc component at luminosities $10^{-6} \lesssim L_X/L_{\rm Edd} \lesssim 10^{-3}$.

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